MEG II実験液体キセノンガンマ線検出器の
時間較正用カウンターを用いた時間分解能評価

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Outline

- **An overview of MEG II experiment**
  - $\mu \to e\gamma$ Search
  - MEG II Experiment

- **Investigation of the systematic errors in the LXe detector timing resolution**
  - Timing resolution evaluation of LXe detector
  - Calculation of σ_{vertex}
  - Result of the vertex measurement

- **The timing resolution evaluation in 2021 CEX run**
  - Timing resolution of LXe detector

- **Summary & prospect**

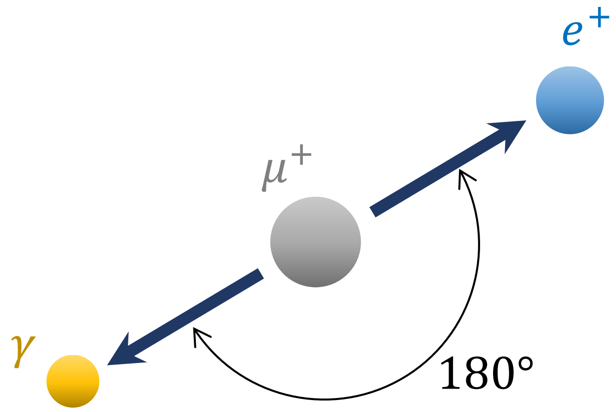
$\mu \rightarrow e\gamma$ Search

- $\mu \rightarrow e\gamma$ is a charged lepton flavor violation decay.
- The decay is almost prohibited in the Standard Model.

  $\mathcal{B}(\mu \rightarrow e\gamma)$: 10^{-54}

  It can be observable in theories beyond SM.

  $\mathcal{B}(\mu \rightarrow e\gamma)$: $10^{-11} \sim 10^{-14}$



- Upper limit on the branching ratio was obtained by the MEG experiment.

  $\mathcal{B}(\mu \rightarrow e\gamma) < 4.2\times10^{-13}$ (90% C. L.)

Signal of $\mu \rightarrow e\gamma$

e^+ and γ are emitted

- simultaneously ←The gamma-ray hit timing needs to be reconstructed with accuracy.
- back-to-back
- at the same energy (52.8 MeV)

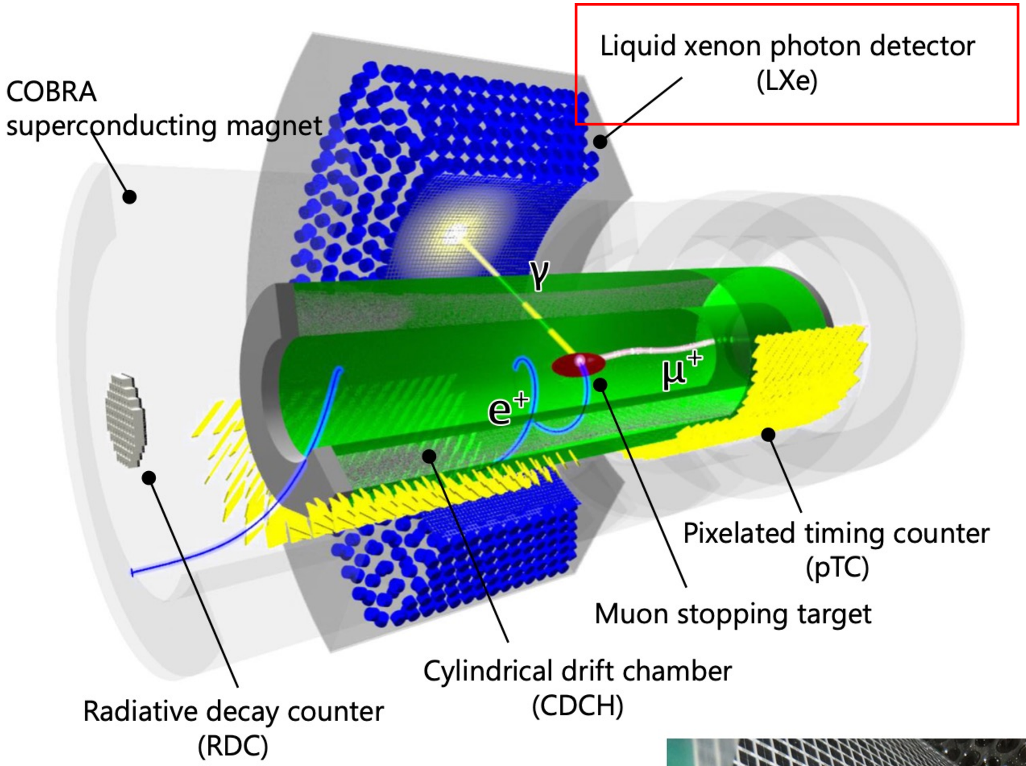
MEG II Experiment

MEG II experiment searches $\mu \to e\gamma$.

Goal : $\mathcal{B}(\mu \to e\gamma) \sim 6\times10^{-14}$

The most intense μ^+ beam

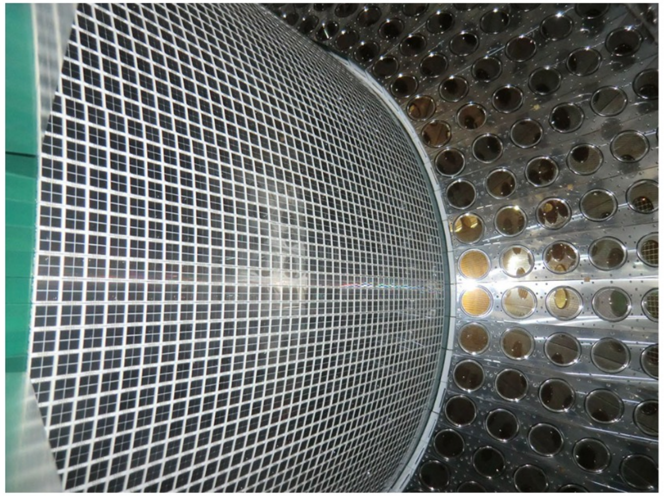
at Paul Scherrer Institute



Liquid xenon (LXe) gamma-ray detector

LXe detector measures the position, energy and timing of the gamma-ray.

4092 VUV-sensitive MPPCs (entrance face) + 668 PMTs (other faces)



Timing Resolution Evaluation of LXe Detector

Charge EXchange reaction (CEX)

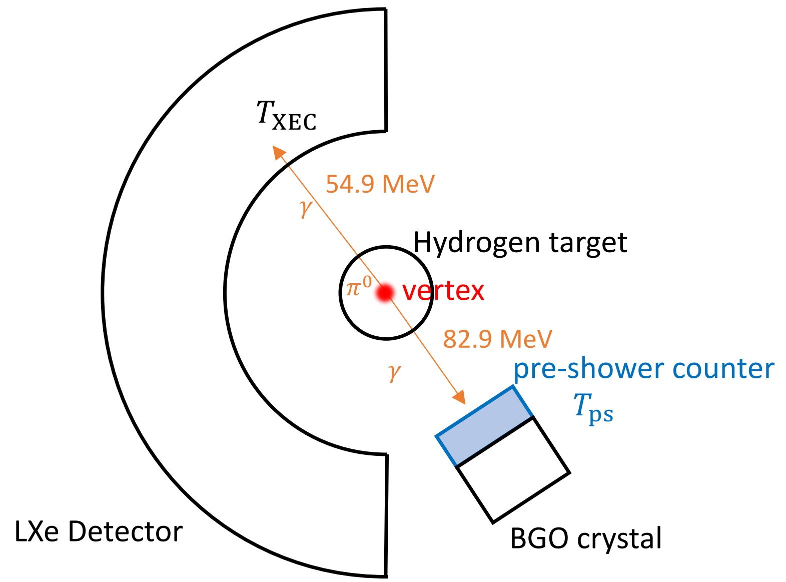
$$\pi^- p \to \pi^0 n$$

$$\pi^0 \to \gamma\gamma$$ (the beam diameter in 2021 CEX run : 4 mm)

π^- is injected into a liquid hydrogen target.

Back-to-back γ-rays : 54.9 MeV and 82.9 MeV

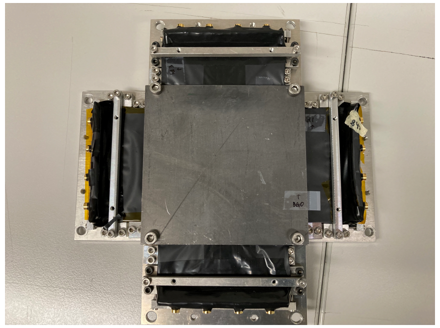
Close to the energy of the signal event (52.8 MeV).

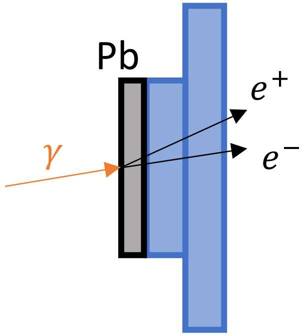


absolute timing resolution $\sigma_{\mathrm{abs}} = \sigma(T_{\mathrm{xec}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{vertex}}$

intrinsic timing resolution $\sigma_{\mathrm{int}} = \sigma(T_{\mathrm{PM,even}} - T_{\mathrm{PM,odd}})/2$

Coherent effects are subtracted in the intrinsic resolution.





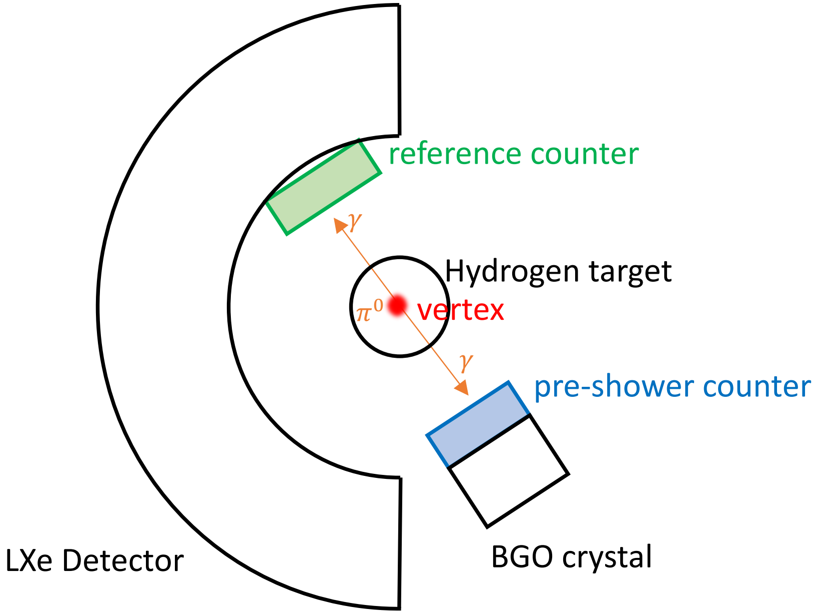
the timing resolution of LXe detector in 2020

	Absolute [ps]	Intrinsic [ps]
Data	82.0	38.5
MC	57.3	38.4

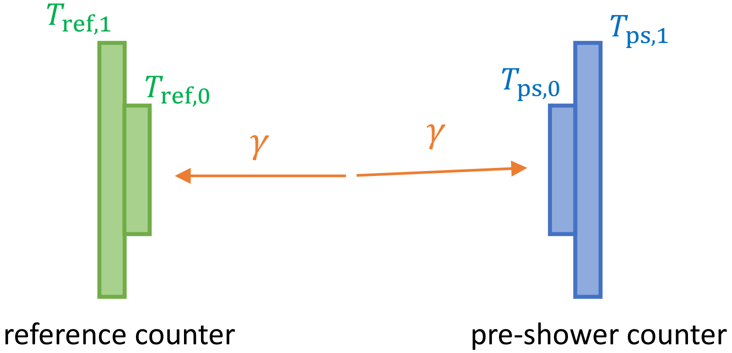
The data of the absolute timing resolution is worse than the result of MC.
One of the possible causes is the contribution from vertex uncertainty.
In this talk, the result of the vertex measurement and the timing resolution of LXe detector in 2021 CEX run.

Calculation of σ_{vertex}

A reference counter was installed in front of LXe detector to measure σ_{vertex}.
The timing resolution of each counter is known. (~40 ps in a lab test)
Evaluate σ_{vertex} using the hit time on each plate.



$$\begin{cases} \sigma\left(\frac{T_{\text{ps},0}+T_{\text{ps},1}}{2} - \frac{T_{\text{ref},0}+T_{\text{ref},1}}{2}\right) = \frac{\sigma_{\text{ps},0}\oplus\sigma_{\text{ps},1}\oplus\sigma_{\text{ref},0}\oplus\sigma_{\text{ref},1}}{2} \oplus \sigma_{\text{vertex}} \\ \sigma(T_{\text{ps},0} - T_{\text{ref},0}) = \sigma_{\text{ps},0} \oplus \sigma_{\text{ref},0} \oplus \sigma_{\text{vertex}} \\ \sigma(T_{\text{ps},1} - T_{\text{ref},1}) = \sigma_{\text{ps},1} \oplus \sigma_{\text{ref},1} \oplus \sigma_{\text{vertex}} \\ \sigma(T_{\text{ps},0} - T_{\text{ref},1}) = \sigma_{\text{ps},0} \oplus \sigma_{\text{ref},1} \oplus \sigma_{\text{vertex}} \\ \sigma(T_{\text{ps},1} - T_{\text{ref},0}) = \sigma_{\text{ps},1} \oplus \sigma_{\text{ref},0} \oplus \sigma_{\text{vertex}} \end{cases}$$

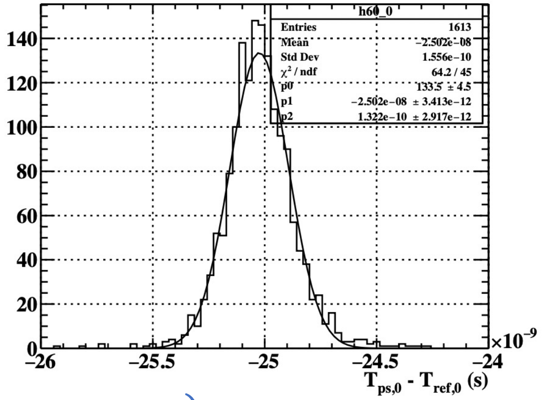


From the above equations, σ_{vertex} is expressed as

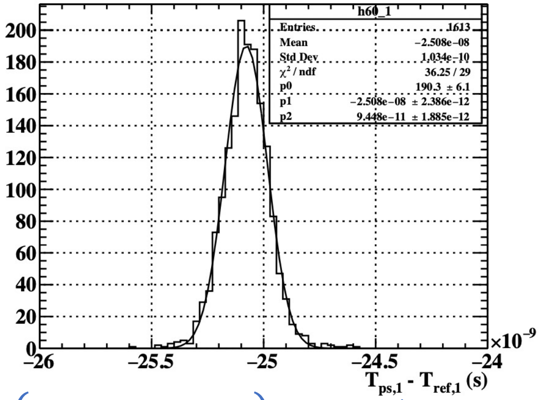
$$\sigma_{\text{vertex}}^2 = 2\sigma^2\left(\frac{T_{\text{ps},0}+T_{\text{ps},1}}{2} - \frac{T_{\text{ref},0}+T_{\text{ref},1}}{2}\right) - \frac{\sigma^2(T_{\text{ps},0} - T_{\text{ref},0}) + \sigma^2(T_{\text{ps},1} - T_{\text{ref},1}) + \sigma^2(T_{\text{ps},0} - T_{\text{ref},1}) + \sigma^2(T_{\text{ps},1} - T_{\text{ref},0})}{4}$$

Result of Vertex Measurement

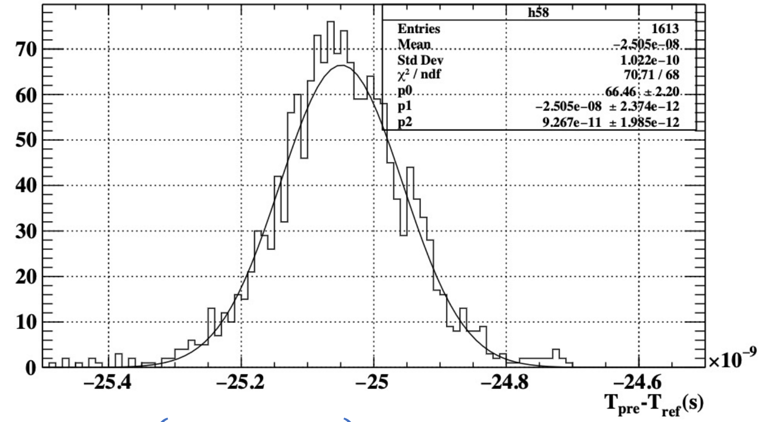
$$\sigma_{\text{vertex}}^2 = 2\sigma^2\left(\frac{T_{\text{ps},0}+T_{\text{ps},1}}{2} - \frac{T_{\text{ref},0}+T_{\text{ref},1}}{2}\right) - \frac{\sigma^2(T_{\text{ps},0}-T_{\text{ref},0}) + \sigma^2(T_{\text{ps},1}-T_{\text{ref},1}) + \sigma^2(T_{\text{ps},0}-T_{\text{ref},1}) + \sigma^2(T_{\text{ps},1}-T_{\text{ref},0})}{4}$$



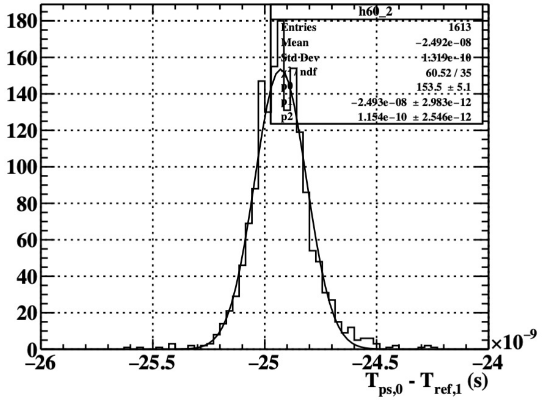
$\sigma(T_{\text{ps},0}-T_{\text{ref},0}) = 132.2 \pm 2.9$ ps



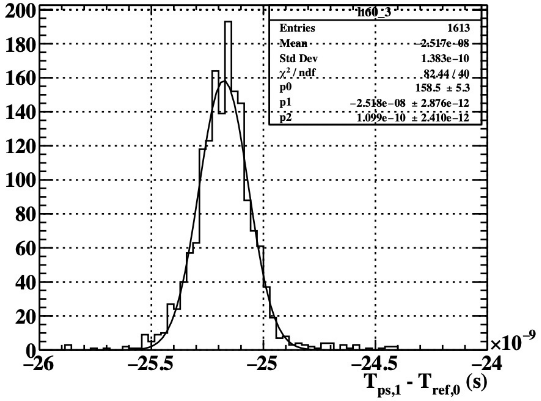
$\sigma(T_{\text{ps},1}-T_{\text{ref},1}) = 94.5 \pm 1.9$ ps



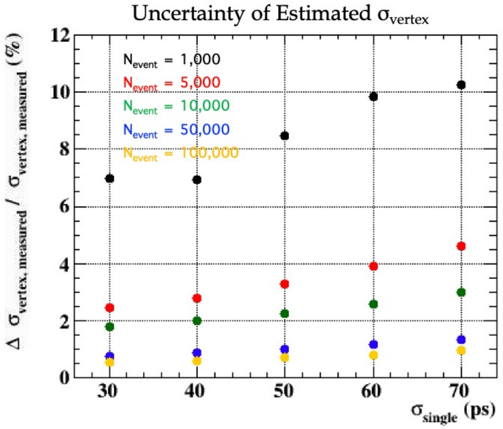
$\sigma(T_{\text{ps}}-T_{\text{ref}}) = 92.7 \pm 2.0$ ps



$\sigma(T_{\text{ps},0}-T_{\text{ref},1}) = 115.4 \pm 2.6$ ps



$\sigma(T_{\text{ps},1}-T_{\text{ref},0}) = 109.9 \pm 2.4$ ps



To estimate σ_{vertex} with 3-5 % precision, 5000 events are needed.

$\boldsymbol{\sigma_{\text{vertex}} = 65.0 \pm 6.1\ \text{ps}\ (9.8 \pm 0.9\ \text{mm})}$

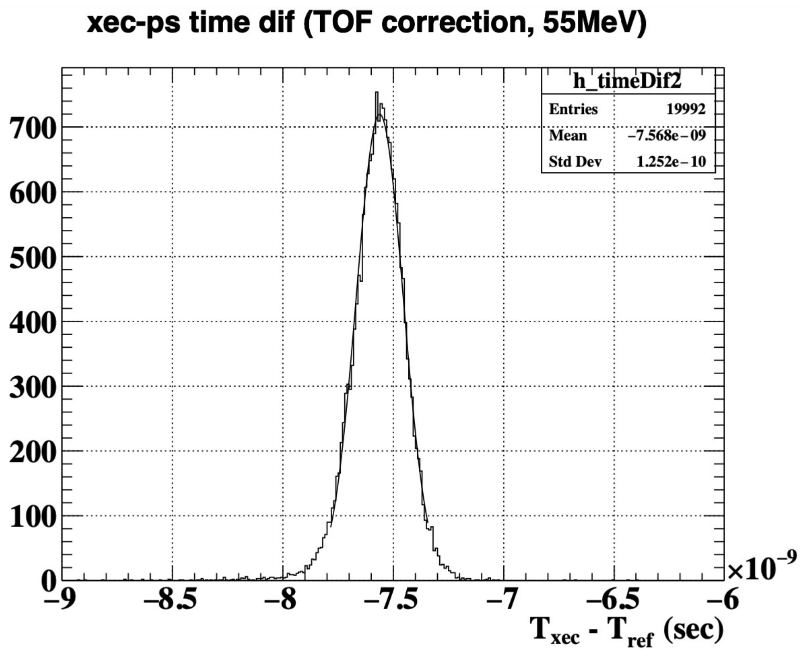
The number of the events obtained is about 1600 due to the limitation of the beamtime and the target stability.

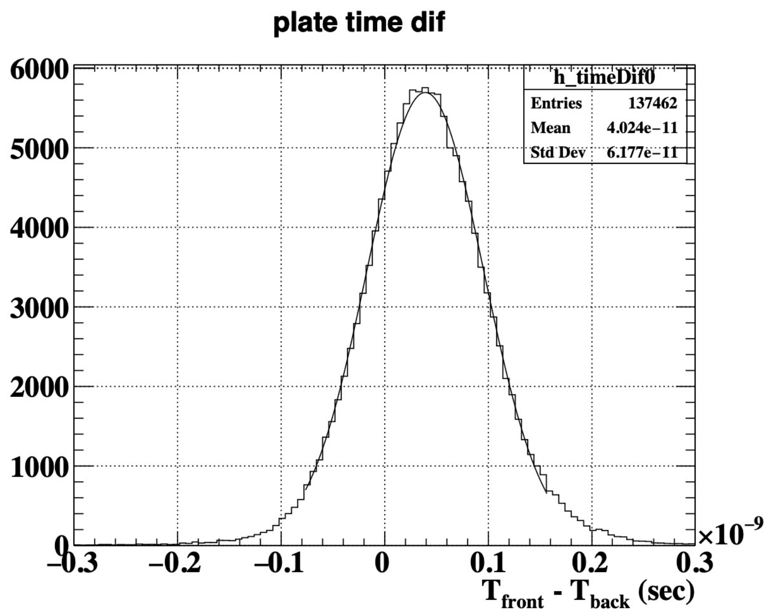
The effect of the electronics used for DAQ has not been considered.

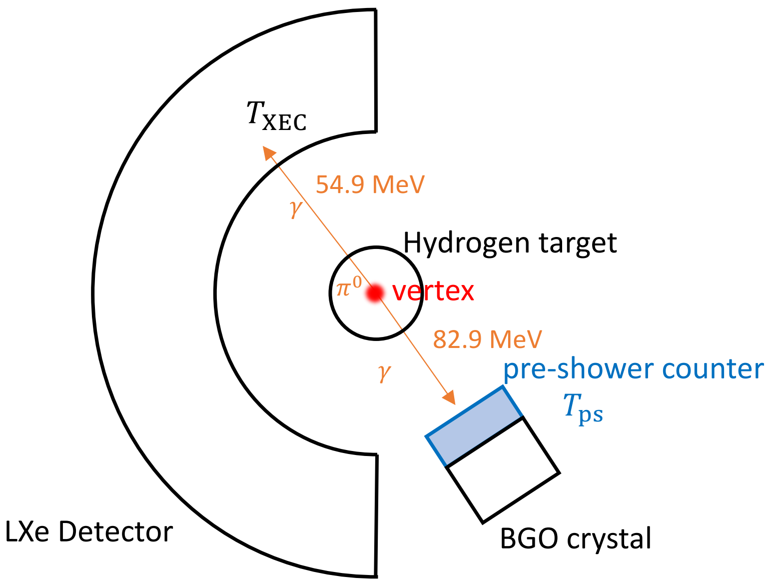
Timing Resolution of LXe Detector

The absolute timing resolution is evaluated using back-to-bask events from CEX.

$$\sigma_{\mathrm{abs}} = \sigma\left(T_{\mathrm{XEC}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}\right) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{vertex}}$$







$\sigma\left(T_{\mathrm{XEC}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}\right) = 106.6 \pm 0.8$ ps

$\sigma_{\mathrm{ps}} = 28.2 \pm 0.1$ ps

$\sigma_{\mathrm{vertex}} = 65.0 \pm 6.1$ ps

$\boldsymbol{\sigma_{\mathrm{abs}} = 79.6 \pm 5.1}$ **ps**

The timing calibration has not been optimized yet.

Summary & Prospect

- The timing resolution of LXe detector is evaluated using CEX reaction.
- One of the possible causes between the difference of the data in 2020 and the MC simulation result is the contribution from vertex uncertainty.
- The new timing counter was installed in front of LXe detector and σ_{vertex} was measured in 2021. The result of the vertex measurement is $\sigma_{\mathrm{vertex}} = 65.0 \pm 6.1$ ps.
- The timing resolution of LXe detector is 79.6 ± 5.1 ps in the current analysis.
- The cause of σ_{vertex} being lager than expected will be investigated by MC simulation.

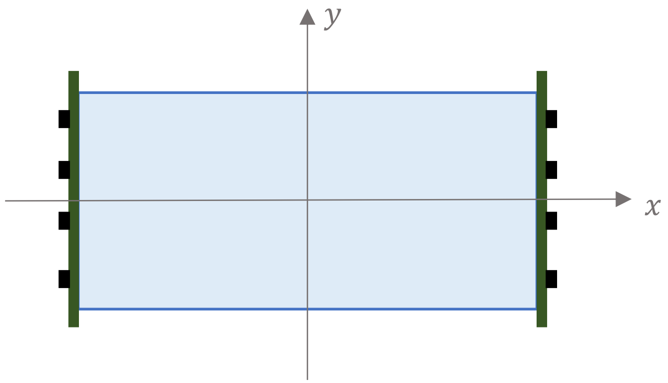
Back up

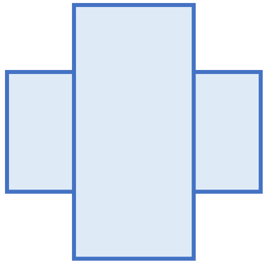
Position Reconstruction

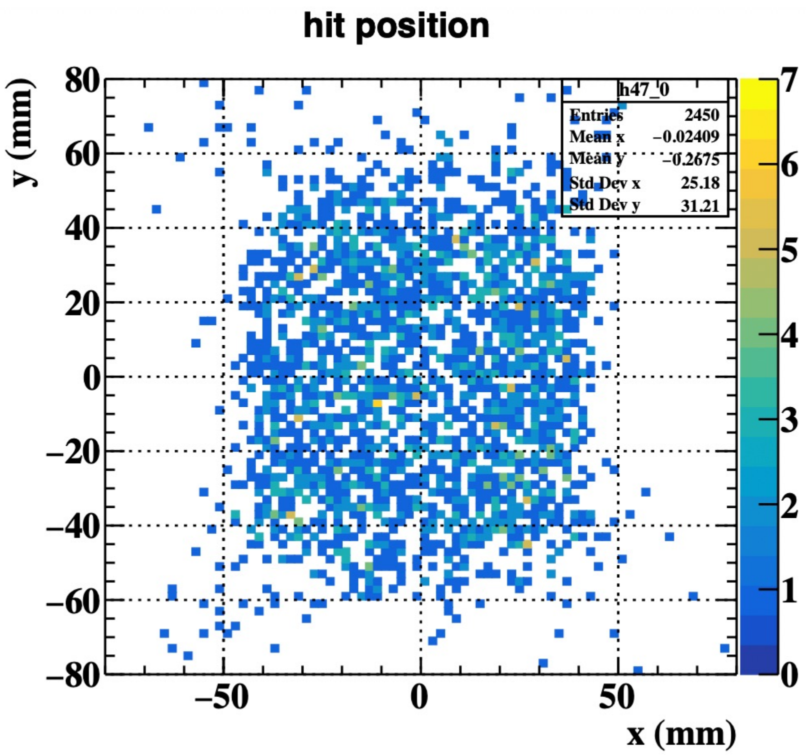
t_r , t_l : the signal time of the right/left channels

$$t_l - t_r = \frac{x + L}{v_c} - \frac{L - x}{v_c} = \frac{2x}{v_c}$$

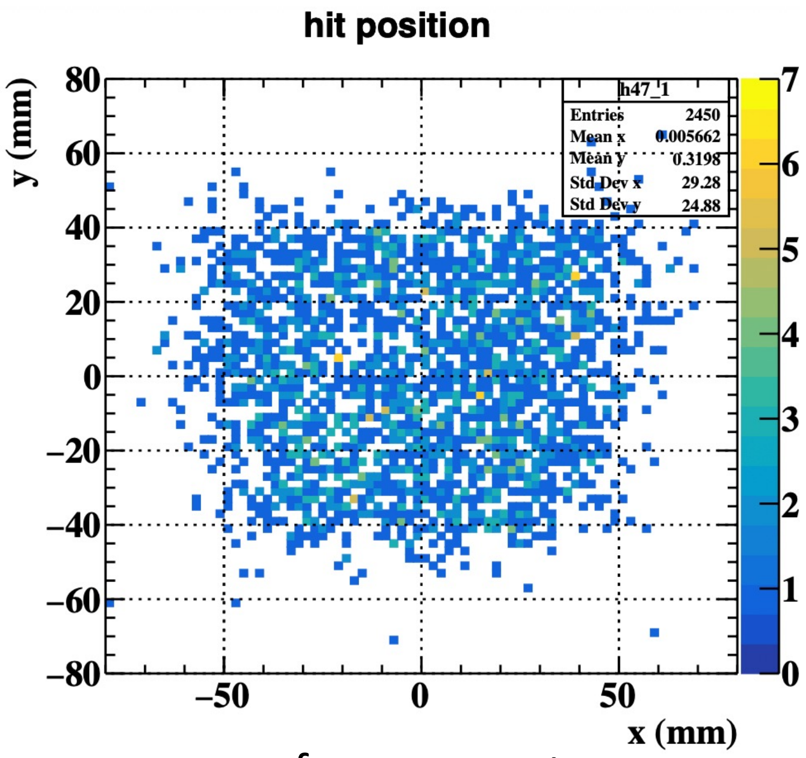
$$x = \frac{v_c(t_l - t_r)}{2}$$







pre-shower counter



reference counter

Methods of vertex analysis

- Method 1

$$\sigma_{\mathrm{vertex}} = \sigma\left(T_{\mathrm{ps}} - T_{\mathrm{ref}}\right) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{ref}}$$

A systematic can be a problem.

- Method 2

$$\sigma_{\mathrm{vertex}} = \sigma\left(T_{\mathrm{ps,0}} - T_{\mathrm{ps,1}}\right) \ominus \sigma_{\mathrm{ps,0}} \ominus \sigma_{\mathrm{ps,1}}$$

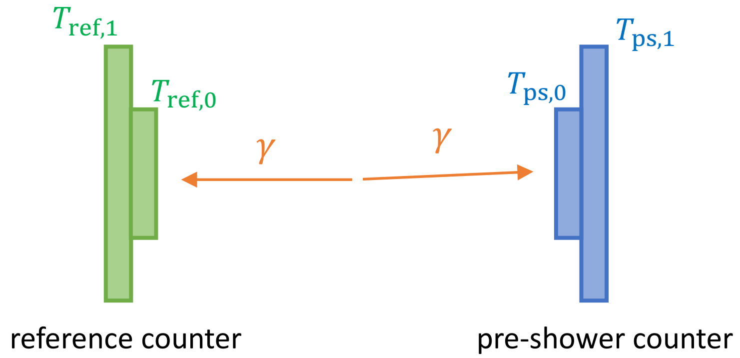
The same event can not be used to evaluated $\sigma\left(T_{\mathrm{ps,0}} - T_{\mathrm{ps,1}}\right)$ and $\sigma_{\mathrm{ps,0}} \oplus \sigma_{\mathrm{ps,1}}$.

- Method 3

$$\sigma_{\mathrm{vertex}}^2 = 2\sigma^2\left(\frac{T_{\mathrm{ps,0}} + T_{\mathrm{ps,1}}}{2} - \frac{T_{\mathrm{ref,0}} + T_{\mathrm{ref,1}}}{2}\right) - \frac{\sigma^2\left(T_{\mathrm{ps,0}} - T_{\mathrm{ref,0}}\right) + \sigma^2\left(T_{\mathrm{ps,1}} - T_{\mathrm{ref,1}}\right) + \sigma^2\left(T_{\mathrm{ps,0}} - T_{\mathrm{ref,1}}\right) + \sigma^2\left(T_{\mathrm{ps,1}} - T_{\mathrm{ref,0}}\right)}{4}$$

σ_{vertex} can be evaluated without any assumptions.

Result of the vertex measurement in method 1



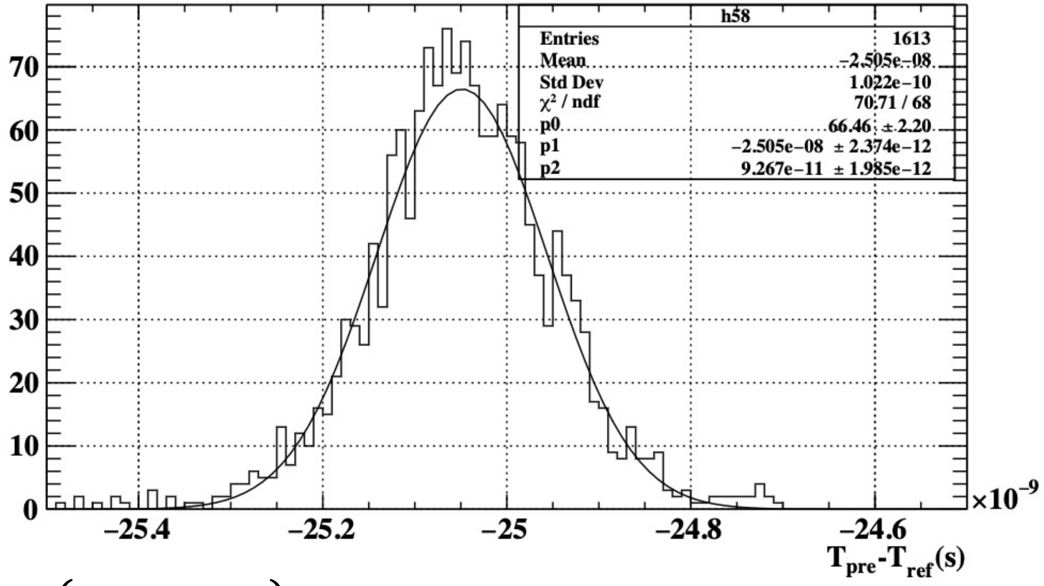
Method 1

$$\sigma_{\mathrm{vertex}} = \sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{ref}}$$

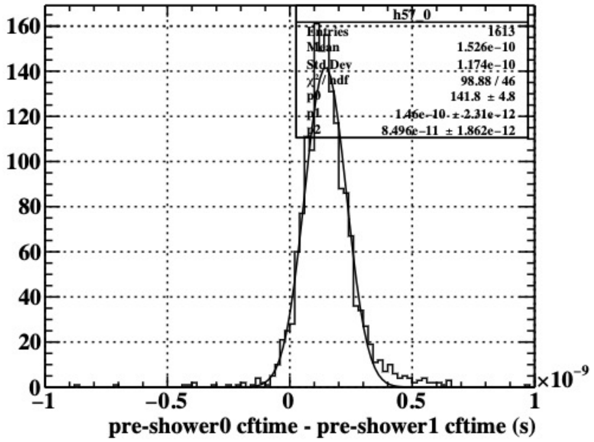
$$\sigma_{\mathrm{ps}} = \sigma\left(\frac{T_{\mathrm{ps},0}+T_{\mathrm{ps},1}}{2}\right) \stackrel{?}{=} \sigma\left(\frac{T_{\mathrm{ps},0}-T_{\mathrm{ps},1}}{2}\right)$$

$$\sigma_{\mathrm{ref}} = \sigma\left(\frac{T_{\mathrm{ref},0}+T_{\mathrm{ref},1}}{2}\right) \stackrel{?}{=} \sigma\left(\frac{T_{\mathrm{ref},0}-T_{\mathrm{ref},1}}{2}\right)$$

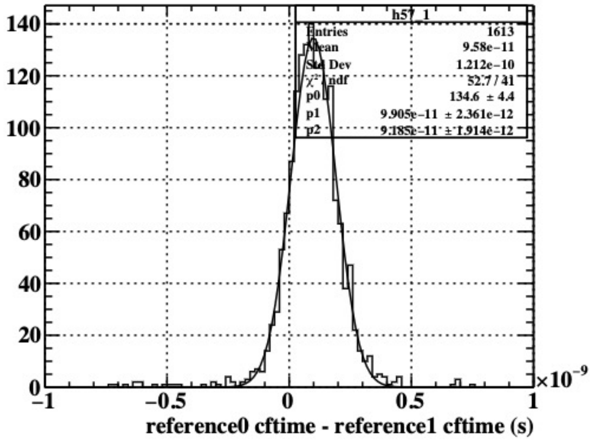
Systematics can be a problem.



$\sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}}) = 92.67 \pm 1.98$ ps



$\sigma_{\mathrm{ps}} = 42.48 \pm 0.931$ ps



$\sigma_{\mathrm{ref}} = 45.93 \pm 0.957$ ps

$$\sigma_{\mathrm{vertex}} = \sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}}) \ominus \sigma_{\mathrm{ps}} \ominus \sigma_{\mathrm{ref}}$$
$$= 68.36 \pm 2.83 \text{ ps}$$

Result of the vertex measurement in method 2

Method 2

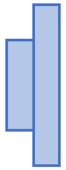
$$\sigma_{\mathrm{vertex}} = \sigma(T_{\mathrm{ps},0} - T_{\mathrm{ps},1}) \ominus \sigma_{\mathrm{ps},0} \ominus \sigma_{\mathrm{ps},1}$$

$$\sigma_{\mathrm{ps},0} \oplus \sigma_{\mathrm{ps},1} = \sigma'(T_{\mathrm{ps},0} - T_{\mathrm{ps},1})$$

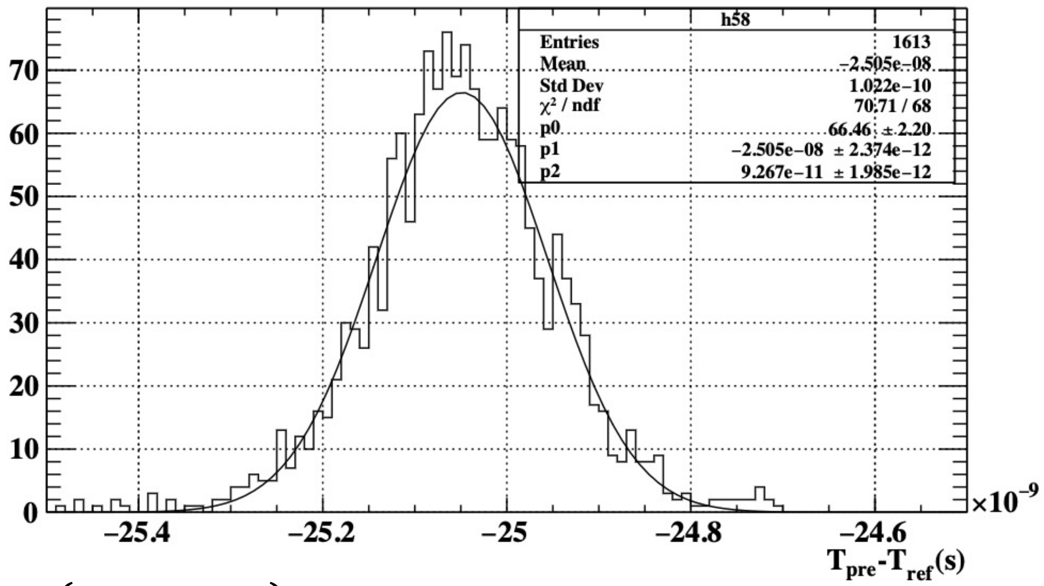
The same event can not be used to evaluated

$\sigma(T_{\mathrm{ps},0} - T_{\mathrm{ps},1})$ and $\sigma_{\mathrm{ps},0} \oplus \sigma_{\mathrm{ps},1}$.

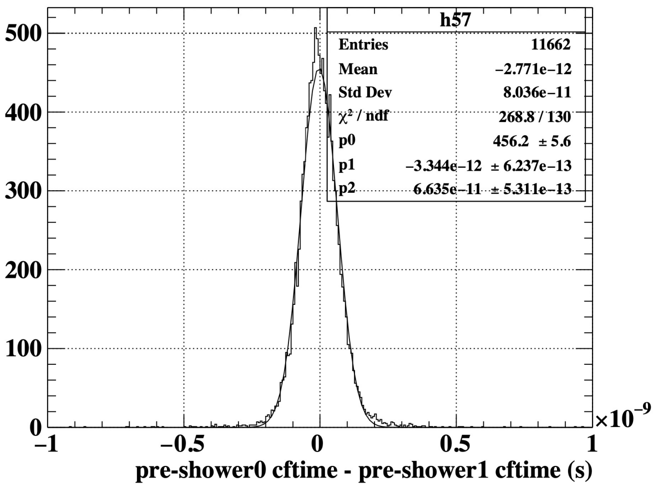
$\sigma(T_{\mathrm{ps},0} - T_{\mathrm{ps},1})$ in vertex measurement

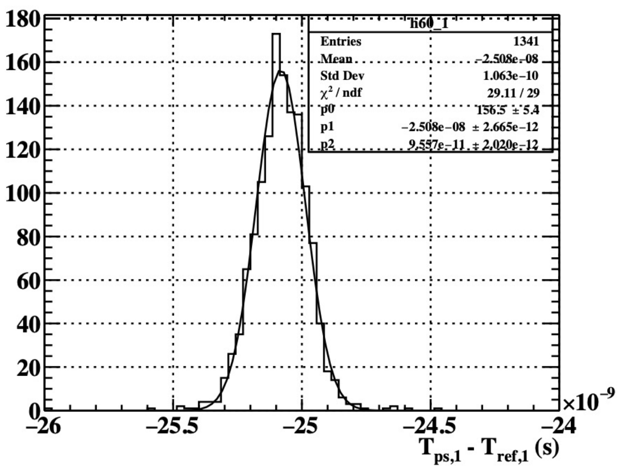


$\sigma'(T_{\mathrm{ps},0} - T_{\mathrm{ps},1})$ in CEX



$\sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}}) = 92.67 \pm 1.98$ ps





$\sigma'(T_{\mathrm{ps},0} - T_{\mathrm{ps},1}) = 66.35 \pm 0.531$ ps

$\sigma(T_{\mathrm{ps},0} - T_{\mathrm{ps},1}) = 94.48 \pm 1.89$ ps

$\sigma_{\mathrm{vertex}} = 68.79 \pm 2.85$ ps

Time dependence of σ_{vertex}

Method 1

$$\sigma_{\text{vertex}} = \sigma(T_{\text{ps}} - T_{\text{ref}}) \ominus \sigma_{\text{ps}} \ominus \sigma_{\text{ref}}$$

	$\sigma(T_{\text{ps}} - T_{\text{ref}})$	σ_{ps}	σ_{ref}	σ_{vertex}
1st period	90.09 ± 3.80	40.55 ± 2.10	44.51 ± 2.02	$\mathbf{67.00 \pm 5.43}$
2nd period	91.62 ± 4.58	38.67 ± 2.03	43.44 ± 1.95	$\mathbf{70.80 \pm 6.15}$
3rd period	91.56 ± 4.35	34.06 ± 3.03	42.20 ± 3.87	$\mathbf{73.78 \pm 6.00}$
All period	92.67 ± 1.98	42.48 ± 0.931	45.93 ± 0.957	$\mathbf{68.36 \pm 2.83}$

Method 2

$$\sigma_{\text{vertex}} = \sigma(T_{\text{ps,0}} - T_{\text{ps,1}}) \ominus \sigma_{\text{ps,0}} \ominus \sigma_{\text{ps,1}}$$

	$\sigma(T_{\text{ps,1}} - T_{\text{ref,1}})$	$\sigma_{\text{ps,0}} \oplus \sigma_{\text{ps,1}} = \sigma'(T_{\text{ps,0}} - T_{\text{ps,1}})$	σ_{vertex}
1st period	98.27 ± 3.67	66.35 ± 0.531	$\mathbf{72.49 \pm 5.01}$
2nd period	98.27 ± 3.67	66.35 ± 0.531	$\mathbf{73.84 \pm 4.94}$
3rd period	96.61 ± 4.90	66.35 ± 0.531	$\mathbf{70.23 \pm 6.76}$
All period	94.48 ± 1.89	66.35 ± 0.531	$\mathbf{68.79 \pm 2.85}$

Time dependence of σ_{vertex}

Method 3

$$\sigma_{vertex}^2 = 2\sigma^2\left(\frac{T_{\mathrm{ps,0}} + T_{\mathrm{ps,1}}}{2} - \frac{T_{\mathrm{ref,0}} + T_{\mathrm{ref,1}}}{2}\right) - \frac{\sigma^2\left(T_{\mathrm{ps,0}} - T_{\mathrm{ref,0}}\right) + \sigma^2\left(T_{\mathrm{ps,1}} - T_{\mathrm{ref,1}}\right) + \sigma^2\left(T_{\mathrm{ps,0}} - T_{\mathrm{ref,1}}\right) + \sigma^2\left(T_{\mathrm{ps,1}} - T_{\mathrm{ref,0}}\right)}{4}$$

	$\sigma(T_{\mathrm{ps}} - T_{\mathrm{ref}})$	$\sigma(T_{\mathrm{ps,0}} - T_{\mathrm{ref,0}})$	$\sigma(T_{\mathrm{ps,1}} - T_{\mathrm{ref,1}})$	$\sigma(T_{\mathrm{ps,0}} - T_{\mathrm{ref,1}})$	$\sigma(T_{\mathrm{ps,1}} - T_{\mathrm{ref,0}})$	σ_{vertex}
1st period	90.09 ± 3.80	128.8 ± 5.25	98.27 ± 3.67	110.9 ± 0.810	103.2 ± 5.15	$\mathbf{62.72 \pm 11.5}$
2nd period	91.62 ± 4.58	129.1 ± 5.63	99.27 ± 3.66	109.0 ± 4.68	118.2 ± 4.60	$\mathbf{60.80 \pm 14.5}$
3rd period	91.56 ± 4.35	114.2 ± 8.34	96.61 ± 4.90	104.8 ± 12.8	85.13 ± 11.3	$\mathbf{81.13 \pm 11.3}$
All period	92.67 ± 1.98	132.2 ± 2.91	94.48 ± 1.89	115.4 ± 2.55	109.9 ± 2.41	$\mathbf{64.98 \pm 6.09}$

Timing Calibration of LXe Detector

The calibration parameters must be extracted to estimate the gamma hit timing.

Define the reference time t_{ref} as follows.

$$t_{\mathrm{ref}} = t_{\mathrm{ps}} + t_{\mathrm{TOF}}$$

1. The time difference dt is calculated for each photosensor **for each group of the photosensors**.

$$dt = t_{\mathrm{pm}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - t_{\mathrm{ref}}$$

the offset effect from the length of the cables

2. The time difference dt is calculated for each photosensor **for each photosensor**.

$$dt = t_{\mathrm{pm}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - t_{\mathrm{ref}}$$

the offset effect from the length of the cables

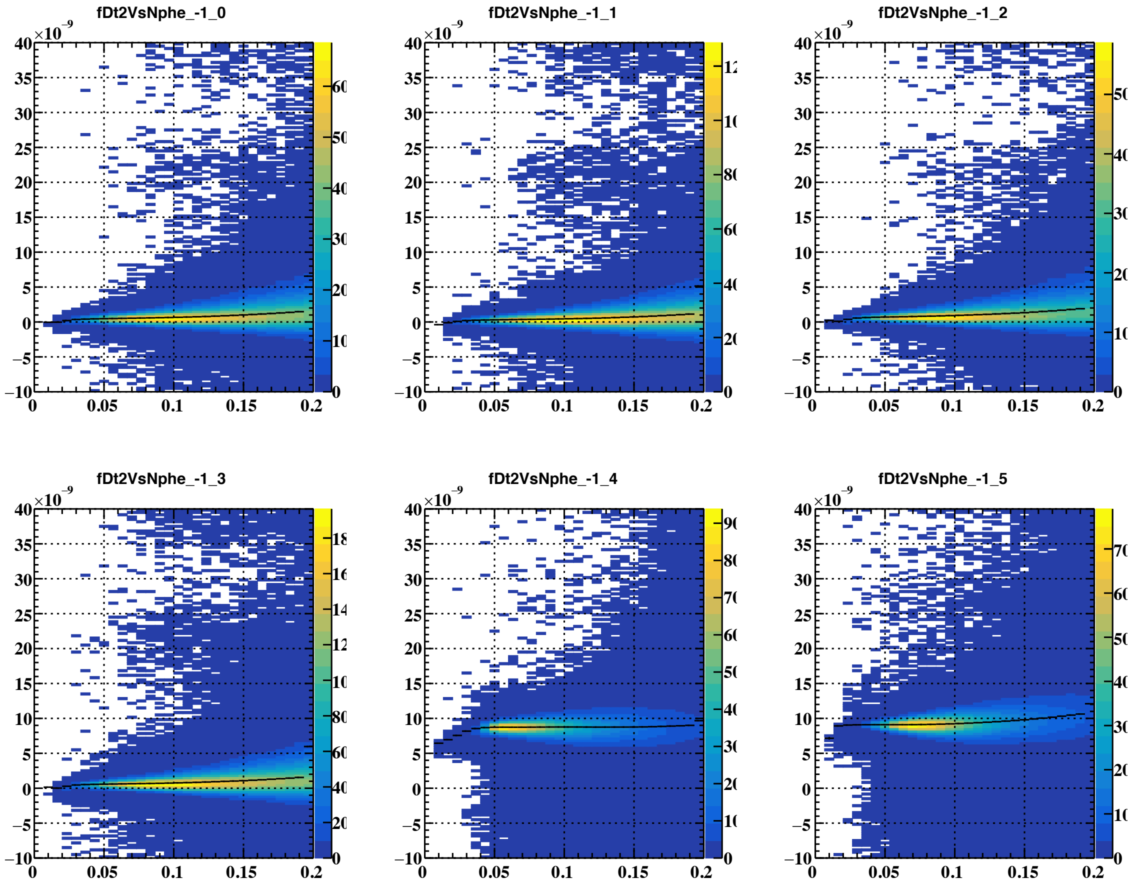
3. The time difference dt is calculated for each photosensor **for each group of the photosensors**.

$$dt = t_{\mathrm{pm}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - t_{\mathrm{ref}}$$

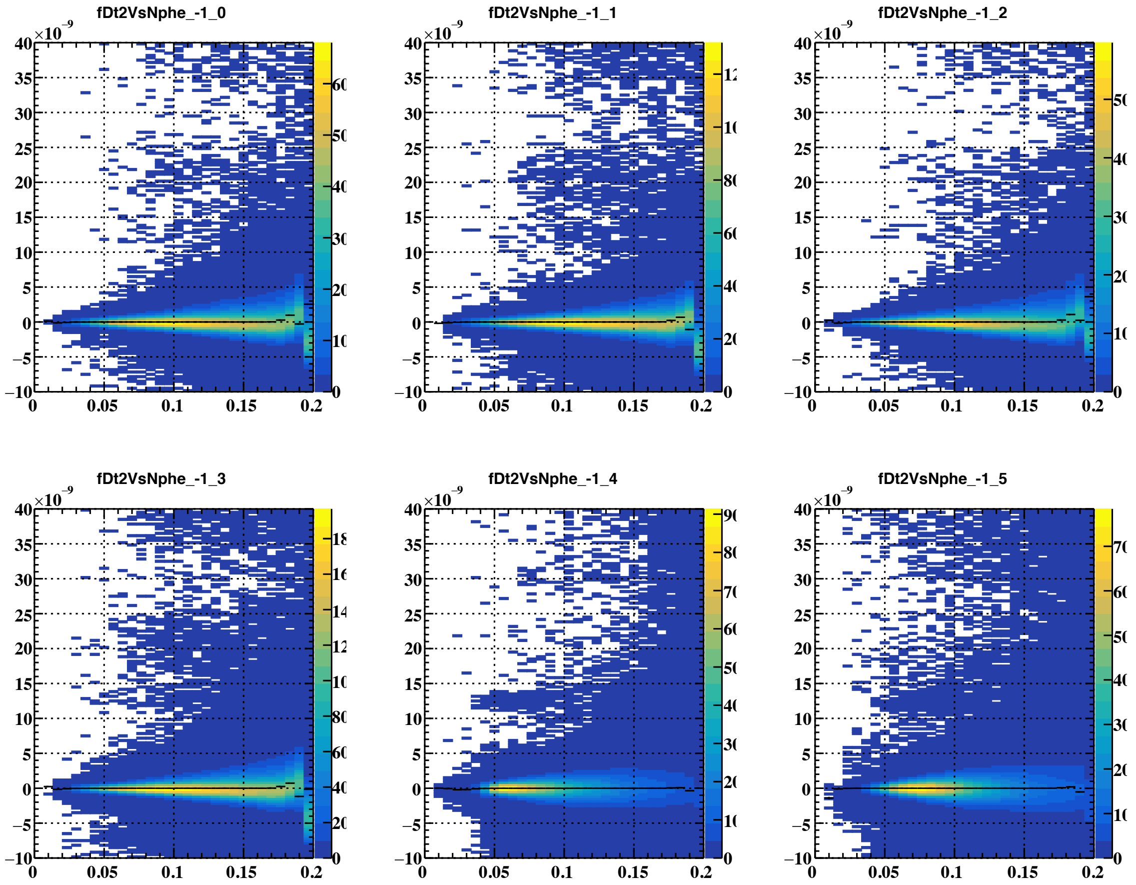
the offset effect from the length of the cables and the rest offset effect

Time Fit

Before the timing calibration



After the timing calibration



Timing Reconstruction in LXe Detector

Gamma hit timing T_{XEC} is reconstructed with χ^2 minimization fit.

$$\chi^2 = \sum_{\mathrm{MPPC,PMT}} \left(\frac{t_{\mathrm{pm}} - t_{\mathrm{walk}} - t_{\mathrm{prop}} - t_{\mathrm{offset}} - T_{\mathrm{XEC}}}{\sigma_{\mathrm{pm}}} \right)^2$$

t_{pm}: the timing of each photosensor

t_{walk}: the time walk effect

t_{prop} : the propagation time of scintillation light from γ hit position to each photosensor

t_{offset} : time offset of each channel

T_{XEC}: the gamma hit timing (fitting parameter)

extracted from data in the timing calibration